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Split comets and the origin of crater chains on Ganymede and Callisto

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When the Voyager 1 spacecraft flew through the jovian system in January 1979, it returned images of several prominent chains of impact craters on the surface of the moon Callisto (Fig. 1). These impressively straight chains, or catenae, are composed of between 4 and 25 craters, and are up to 620 km long. They were initially thought to be secondary craters produced by debris from a larger primary impact[1], but detailed searches for source craters have been largely unsuccessful: a satisfactory explanation for the crater chains has yet to be found. Inspired by the recent observations of comet Shoemaker–Levy 9, which split into a line of about 20 fragments as it swept past Jupiter[2], we suggest that the impact of previous split comets might be responsible for at least some of the catenae on Callisto. In support of this hypothesis, we find that nearly all of Callisto's crater chains are on the Jupiter-facing hemisphere, as are an additional three catenae that we have found on Ganymede. We present a simple model of tidal breakup which both reproduces the range of observed chain lengths and indicates that the parent comets responsible for the Callisto catenae were typically no more than about 10 km in diameter.

If crater chains on Callisto are created by the impact of tidally split comets, a number of testable consequences immediately follow. First, because comets' or asteroids' orbits through the jovian system are generally hyperbolic (Shoemaker–Levy 9 is an exception), the impact of a fragment chain on one of Jupiter's tidally locked satellites should generally occur on the Jupiter-facing side. (Note that we cannot distinguish between comets and asteroids from the crater chains alone; in the following text we use the term 'comet' for either class of object.) Thirteen crater chains that are not obviously secondary to large basins have been recognized on the 70% of Callisto's surface that has been imaged. Of these, 11 are on the Jupiter-facing hemisphere and one is just over the edge on the opposite (anti-Jupiter) hemisphere. The single chain that is near the centre of the anti-Jupiter hemisphere contains a number of highly elliptical craters and is morphologically distinct from all the other chains. Furthermore, if such split comets strike Callisto at its distance of 26.2 R_J from Jupiter (R_J is the radius of Jupiter, 71,400 km), some crater chains should also be visible on Ganymede, at a range of 14.9 R_J. We have found three such chains on the Jupiter-facing hemisphere of Ganymede. Although a few crater chains also occur on the opposite hemisphere, these are secondary to the large craters Halieus and Gilgamesh. The smaller number of crater chains on Ganymede may be explained by its younger surface. At Ganymede's smaller range from Jupiter, however, we expect the chains to be shorter, as the fragments do not have as much time to separate after their parent is tidally disrupted inside Jupiter's Roche limit (the zone within which tidal forces tending to disrupt a small body exceed self-gravitational binding forces[3], which lies at 2.67 R_J for comets of density 1 g cm^{-3}). Figure 2 shows the statistics of crater chain length on Ganymede and Callisto. Although the chains of Ganymede are small in number, they are on average shorter than the chains on Callisto.

FIG. 1 Illustration of a crater chain overprinting the rings of the Valhalla basin on Callisto. The chain is ~340 km long. Voyager image no. FDS 16424.32. This image was enhanced by a de-smearing algorithm written by M. Hicks.

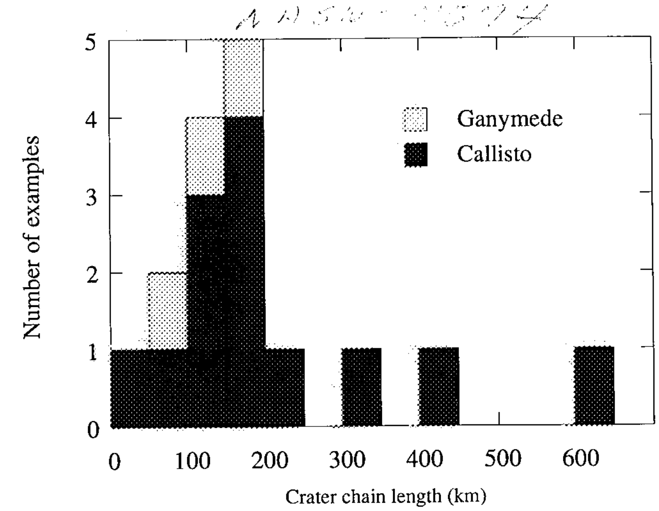

FIG. 2 Histogram showing the lengths and number of crater chains that are not obviously associated with primary craters on Ganymede and Callisto. Note that, on average, crater chains on Ganymede are shorter than those on Callisto, although statistics are poor.

We constructed a model of comet splitting, and investigated the separation of the fragments as a function of several parameters to investigate further the possibility that the crater chains on Ganymede and Callisto are created by split comets. These parameters include initial comet size, closeness of approach to Jupiter, and initial velocity of approach far from Jupiter. Comets rotate with periods long compared to the time of passage inside the Roche limit. For example, the period of comet Halley is now estimated[4] as ~53 h (although with some uncertainty) whereas even slow (parabolic) comets spend at most ~1 h inside the Roche limit. Rotation can therefore be neglected for this problem.

The tidal stresses induced in either spherical[5] or even ellipsoidal[6] elastic bodies have tensional axes parallel to the radius vector. This stress state tends to separate the body along planes normal to the radius vector[7]. We therefore modelled the tidal disruption of a comet by assuming that it breaks into a number of fragments at the point of closest approach to Jupiter, where tidal stresses are greatest. This is an approximation, but it probably makes little difference if disruption actually occurs a little before or after closest approach. When the comet breaks up, we trace the orbits of the two extreme fragments that are broken off at $R_{min}+r_{comet}$ and $R_{min}-r_{comet}$, where R_{min} is the distance of the closest approach to Jupiter and r_{comet} is the radius

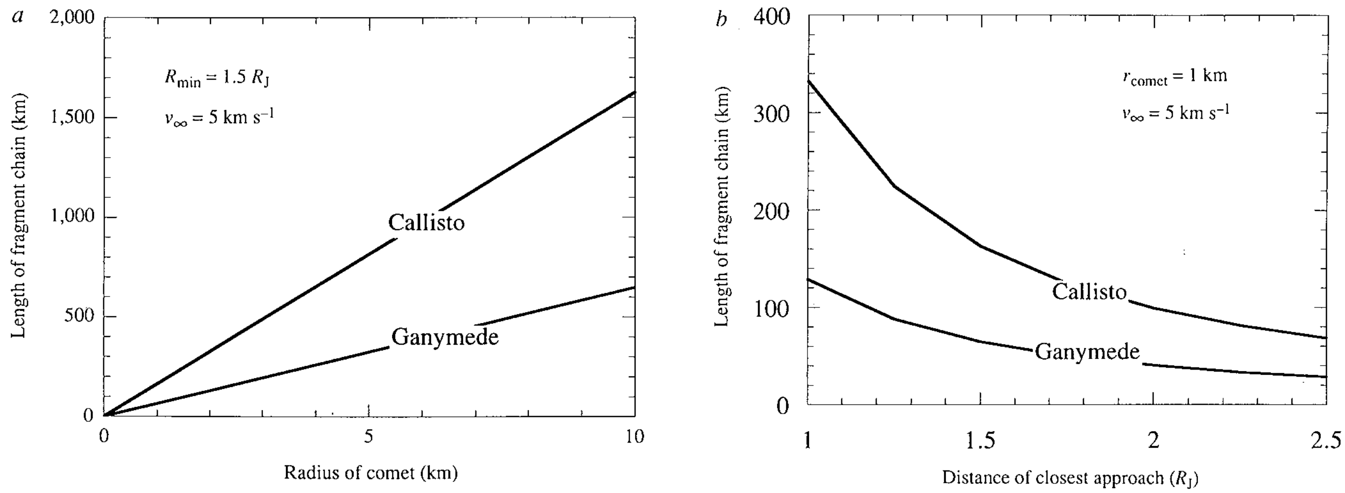

FIG. 3 Results of modelling the orbital evolution of a chain of fragments from a comet split by tides during a close approach to Jupiter. *a* Illustrates how the length of the fragment chain depends on the initial comet radius for impacts on either Ganymede or Callisto. R_{min} is the distance of closest approach to Jupiter and v_∞ is the approach velocity of the comet to Jupiter at great distance. *b* Illustrates how the fragment chain length depends on the distance of closest approach to Jupiter, in units of jovian radii, R_J for a comet of radius $r_{comet} = 1$ km.

of the comet. The initial velocity assigned to the fragments is zero with respect to their mutual centre of mass; the entire difference between their subsequent orbital paths is due to their slightly different starting positions and, to a lesser extent, the approach velocity of their parent comet. Cometary rotation would actually give the different fragments slightly different initial velocities, but this effect is small compared with the other uncertainties. We followed the subsequent dispersion of the fragments using a fifth-order adaptable Runge–Kutta integrator[8] for the centre of gravity of the fragments and for their relative separation. The equation of motion was expanded and linearized about the centre of mass, a sufficient approximation so long as the fragment separation is small compared to the distance to Jupiter, which was true in all cases studied.

The fragments from the split comet form a well defined line in space only for this model of radial breakup. We also constructed a model of rotational bursting of a comet in which tidal stresses are presumed to trigger instantaneous disintegration of a rotating comet, with the fragments flying off in the former equatorial plane with initial velocities determined by the speed of rotation. In this model the fragments formed an elongated loop, not a line. Although the aspect ratio of this loop is large at Callisto, often 6 : 1, the impact of such a loop would not produce the observed straight crater chains. The apparently linear dispersion of the fragments from comet Shoemaker–Levy 9 therefore suggests a radially separated breakup mode. Moreover, a detailed application of the radial breakup model to Shoemaker–Levy 9 gives excellent agreement between the predicted and observed locations of the fragments[9].

Figure 3 shows the predicted lengths of a fragment chain at the orbits of Ganymede and Callisto for comets travelling directly from perijove to the satellite: fragment dispersion becomes so large after this first pass that fragments in orbit about Jupiter would not form continuous crater chains on the satellites. Figure 3*a* shows that the dispersion is a linear function of comet radius, and is about twice as large at Callisto as at Ganymede. Because the ~20–37 km diameter craters in Gipul catena were probably made by objects a few kilometres in diameter, and may thus have evolved from a parent comet ~5 km in diameter, the predicted chain length of 400 km in this figure is consistent with the observed 620 km length, given the variability in the angle at which the line of fragments strikes the surface and the distance of closest approach to Jupiter (assumed to be 1.5 R_J in Fig. 3*a*). Figure 3*b* shows the dependence of fragment chain length on distance of closest approach to Jupiter for a comet of radius 1 km (comparable to the currently estimated dimensions[9] of Shoemaker–Levy 9). The predicted crater chain lengths are comparable to those observed, suggesting that most such chains are made by comets in this size range. This figure indicates that the dispersion is inversely proportional to encounter distance, but that the dispersion at Ganymede is about half that on Callisto under similar conditions. Varying the velocity of approach shows that the dependence of chain length on this factor is weak (~30% decrease) when approach velocities are varied from 0 to ~10 km s^{-1}. The dispersion then decreases by about a factor of two at 20 km s^{-1} (the maximum Jupiter approach velocity for comets bound to the sun is 31 km s^{-1}). The dependence of chain length on approach velocity is thus not as strong as the dependence on initial comet size or distance of closest approach to Jupiter.

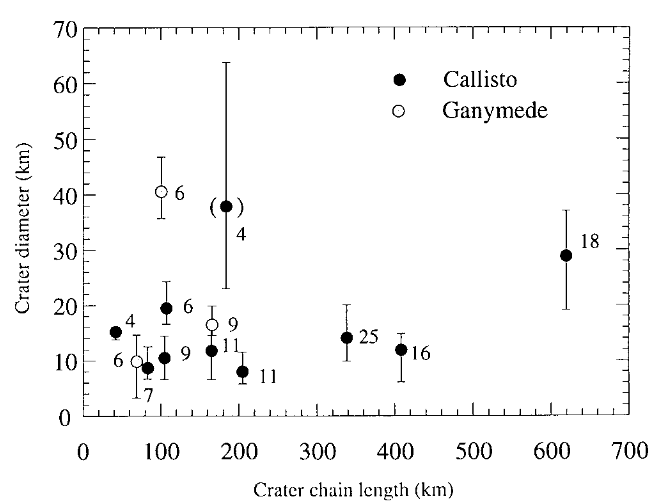

FIG. 4 Correlation between crater chain length and crater diameter for crater chains on Ganymede (open circles with points) and Callisto (solid circles). 'Error bars' indicate the range between maximum and minimum crater sizes; the symbol indicates the average. The number next to each symbol indicates the number of craters in the chain. The data point surrounded by parentheses is not on the Jupiter-facing hemisphere of Callisto and thus may be secondary to some unseen basin.

Assuming that the size of the fragments scale with the size of the parent bodies, the simple model presented here predicts that there should be a positive correlation between crater chain length and crater size. (Considerable scatter should occur because of varying angles of encounter between the fragment chain and satellite surface, encounter distance, velocity of approach, and the number of fragments formed.) A very rough correlation between crater chain length and average crater diameter per chain on Ganymede and Callisto may be present when chains with similar numbers of craters are compared (Fig. 4: note that only ten crater chains on Callisto are plotted because poor image quality prevents accurate diameter measurements on three chains). For a given chain length, there is also a tendency for average crater diameter to increase as the number of craters (and hence comet fragments) per chain decreases, as expected from volume conservation. The order of magnitude of the dispersion is also consistent with the comet splitting model.

On the other hand, this correlation depends in large part on the single data point for the 620-km-long Gipul catena. An alternative interpretation of Fig. 4 is that the craters of nearly all the chains in Fig. 4 are ~10 km in diameter, with the exception of the craters in Gipul. In this interpretation the parent comets are viewed as loose aggregations of pre-existing fragments that are all roughly the same size. Such loose aggregations would then be dispersed by the weak tidal forces during passage inside the Roche limit, as has been suggested[9] for comet Shoemaker–Levy 9. Small parent comets would thus contain only a few such fragments, and large parents would contain many. Gipul's parent must have contained exceptionally large fragments.

If crater chains on Ganymede and Callisto are created by tidally split comets, they preserve a fossil time record of the occurrence and characteristics of comet fragmentation. We estimate the recurrence interval between comet-splitting events from the number of crater chains that have accumulated on the surface of Callisto, assuming a constant cratering rate since the surface formed ~4.0 Gyr ago. Voyager produced adequate images of 70% of the Jupiter-facing hemisphere of Callisto. If it is assumed that the observed 12 crater chains were all produced by split comets, and that comets are equally likely to approach Jupiter from all directions, then the following relation may be deduced. The number of comets that have split near Jupiter is larger than the number on the surface of Callisto by the ratio between the area of a sphere of radius equal to the radius of Callisto's orbit and the projected surface area of Callisto (neglecting gravitational focusing). This relation yields an estimate of $\sim 4.9 \times 10^7$ split comets over a period of 4 Gyr, or a recurrence interval of ~80 yr between splitting events, which is consistent with the obervation of the splitting of comet Brooks 2 near Jupiter in 1886 (ref. 10). □

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